CHARACTERIZATION OF A MICROMACHINED INCHWORM MOTOR WITH THERMOELASTIC LINKAGE ACTUATORS

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ABSTRACT

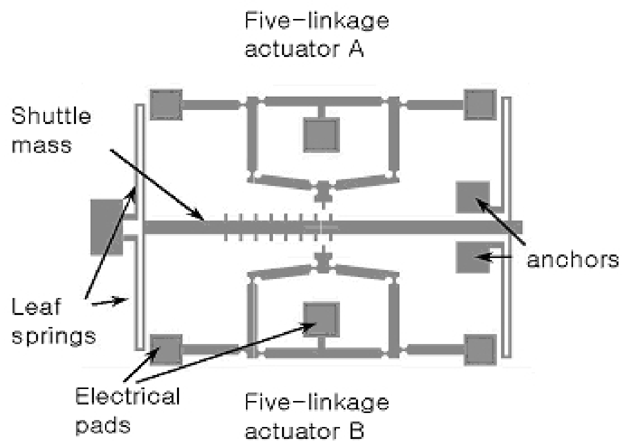
A new micromachined inchworm motor has been designed and fabricated for micro assembly applications. In order to implement inchworm motions, two thermoelastic actuators are contrived to have five-linkage mechanism with two-dimensional motions in tangential and normal directions. The thermoelastic actuators consist of two amplification bars and two coupling bars with four hinge springs. A forked tip, located on the apex of the linkage, is used to fit the teeth of shuttle mass for inchworm operation. The thermal expansion of the active bars generates the displacement of the actuator, which is then transformed into a bending of the active hinges to be finally amplified by the amplification bar. The inchworm actuator progressed by the designed steps of 5 um and latched up by the teeth. The estimated driving force was 50 uN with less than 0.2 um tolerance.

INTRODUCTION

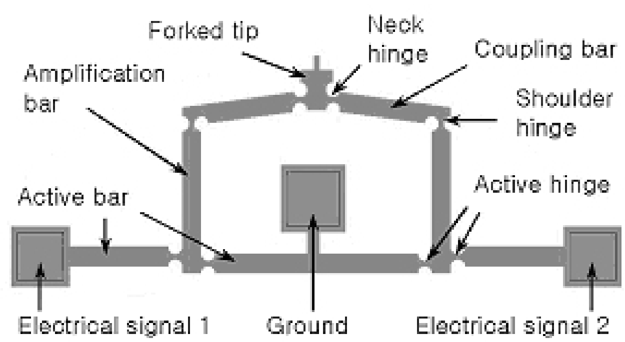
For micro assembly applications, an actuator should be able to translate a small workpiece with an appropriate chucking force without dropping the workpiece during operation [1]. The micro chuck needs a gripping force greater than several tens of uN to grip the workpiece and a stroke longer than 50um. In order to realize a high precision and long stroke translation system, electrostatic driven comb drivers and inchworm motors have been suggested as driving actuators [2][3][4]. Unfortunately, the driving force of electrostatic actuators tends to be small, and it is necessary to apply a high voltage to attain a large displacement. Meanwhile, a thermoelastic actuator was fabricated for considerably large force and long stroke applications [5]. However, this actuator still provides insufficient force and non-rectilinear motion. As a new approach, a linear microengine was demonstrated as an application of bent-beam electrothermal actuation [6]. Even though the driving distance was large enough, its controllable motion was limited to only one-direction. In this work, a new micromachined inchworm motor has been designed, fabricated and characterized for micro assembly applications in the views of high force, long stroke, and two-directional movability.

DESIGN OF THE INCHWORM MOTOR

In order to implement inchworm motions, one pair of thermoelastic actuator are contrived to have a linkage mechanism with two-dimensional motions in tangential and normal directions. The proposed inchworm motor consists of one shuttle mass suspended by four leaf springs and a pair of five-linkage actuators, as shown in Fig. 1(a) [7]. The five-linkage mechanism provides the motion of two degree of freedom using two active hinge points, two shoulder hinges, and one neck hinge. In order to grip the shuttle mass additional neck hinge and the forked tip (end-effector) were added. As the link between two neck hinges is very short, it eventually works as one hinge point. Therefore we can consider the proposed mechanism as a five-linkage system.



(a)



(b)

Figure 1. *Schematics of proposed inchworm motor with thermoelastic actuators, (a) overall view of the inchworm motor, and (b) five-linkage mechanism for 2-dim actuation.*

When an input voltage signal is applied to two electrical pads of the actuator, induced electric current flow raises the temperature of two active bars and two active hinges, and amplified displacement can be obtained from the thermal expansion of active bars and rotation of the amplification bar.

If the two amplification bars rotate in-phase, the forked tip will either move leftward/ rightward with/without the shuttle mass or return to its initial state, as shown in Fig. 2(b), (d) and (f), respectively. On the contrary, if the two amplification bars rotate out-of-phase, the forked tip moves either inward for fitting or outward for releasing the shuttle mass, as shown in Fig. 2(c) and (e), respectively.

One pair of actuators is capable of four kinds of motions, such as fitting a forked tip, rectilinear driving of shuttle mass, releasing the shuttle mass, and returning to its initial state, as illustrated in Fig. 3. In this way, one cycle of stepping motions enables the inchworm motor to have a large stroke by accumulating many stepping movements. In addition, the teeth may reduce power consumption by latch-up after driving. Additionally, the shuttle mass will be moved back when the sequence of the applied signals is reversed. To secure the actuation without slipping, we contrived the teeth structure at the interface between the shuttle mass and the forked tip as shown in Fig. 4(a). We can design the teeth to have shape of "T" for latch up after driving as shown in Fig. 4(b)

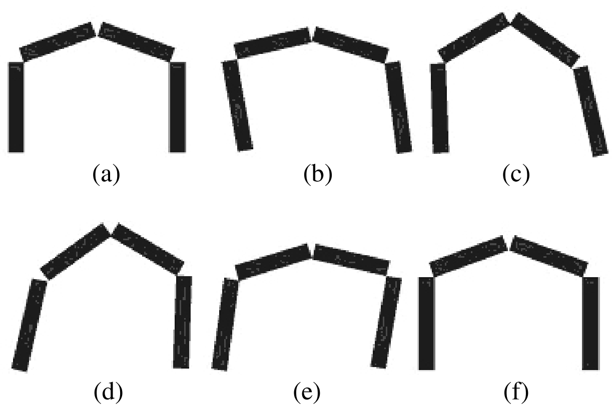
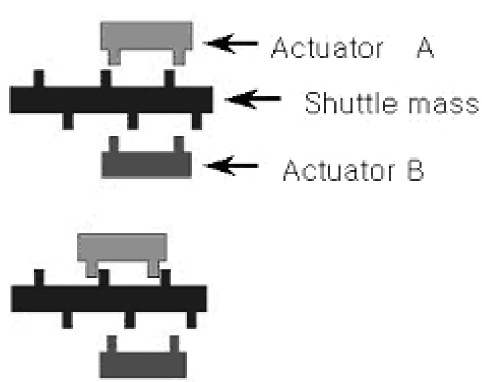


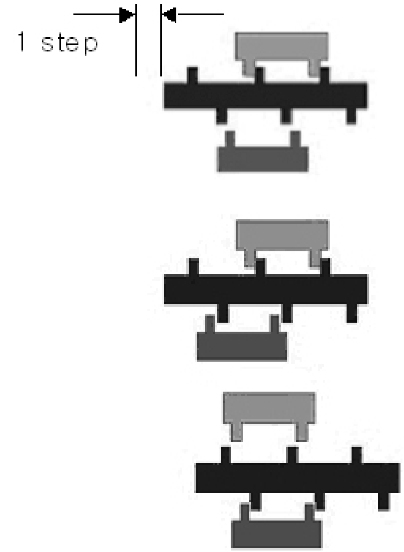
Figure 2. *Schematic unit step motions of the linkage mechanism, (a) initial state, (b) leftward motion, (c) closing motion for fitting, (d) rightward motion for driving, (e) opening motion for releasing, and (f) in-phase leftward motion for returning to initial state.*

(a)



(b)

(c)



(d)

(e)

Figure 3. *Schematic of inchworm actuation with forked tips, (a) initial state, (b) fitting of the forked tip into the shuttle mass by actuator A, (c) rightward driving by actuator A, (d) fitting by actuator B, and (e) extracting and returning to initial state by actuator A, and rightward driving by actuator B.*

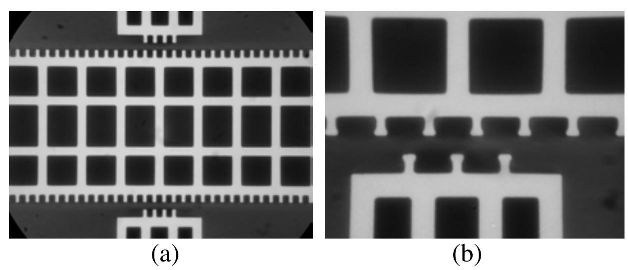


Figure 4. *Photograph images of the fabricated teeth at the interface of shuttle mass and forked tips, (a) plane teeth, and (b) "T" shaped teeth for latch up.*

THEORETICAL ANALYSIS

Operational schemes

In order to utilize the proposed thermoelastic actuator for inchworm motors, the required trajectory was investigated for one cycle of operation, as illustrated in Fig. 5. The trajectory consists of 4 unit steps, such as 1) extrusion for fitting, 2) driving for transportation, 3) retraction for release, and 4) contraction to initial location. The required voltages for right and left linkage actuators to perform inchworm motion according to the cyclic sequence has been shown in Fig. 5. We can see from the diagram that the required strokes are about 5 um and 2 um in tangential and normal directions, respectively.

Stiffness of the actuator

The stiffness at the top of the forked tip is used to estimate the maximum force that the thermoelastic actuator can exert to the shuttle mass. The resultant stiffness of the forked tip can be estimated to be 286 N/m from FEA. We also found that the actuator can generate a driving force over 50 uN with a placement tolerance of 0.2 um.

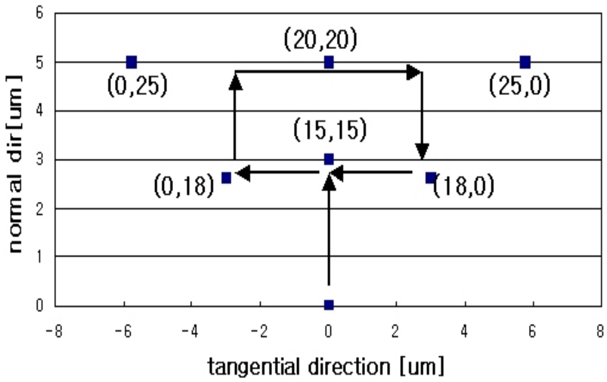


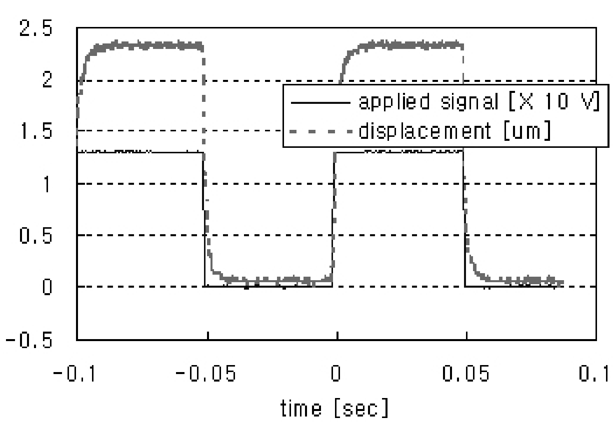
Figure 5. *One cyclic estimated trajectory of five-linkage actuator for inchworm actuation based on FEA. Values in the parentheses are applied voltage to the electrodes for simulation of the trajectory.*

DEVICE FABRICATION

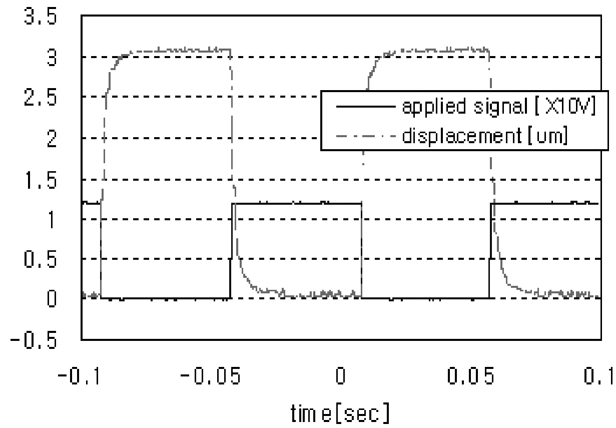
We fabricated the proposed thermoelastic actuators using SOI (silicon-on-insulator) wafers. The minimum feature size was 2 um, which corresponds to the width of one tooth. The device layer of 40 um in thickness was micromachined with DRIE (Deep Reactive Ion Etching) process and was doped with phosphorus to control its electrical resistance. The sacrificial oxide layer was removed using HF GPE (Gas-Phase etching) process with no virtual stiction of microstructures.

EXPERIMENTAL CHARACTERIZATION

Fabricated five-linkage actuators and the inchworm motor have been experimentally characterized and evaluated. The step response of the five-linkage actuators are shown in the Fig. 6(a) and (b) in the tangential and normal direction, respectively. The response times are about 4 msec by 90% of the rising time criterion from step response.



(a)



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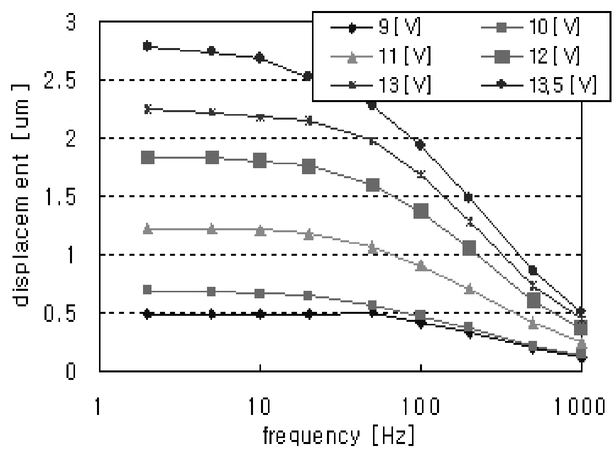


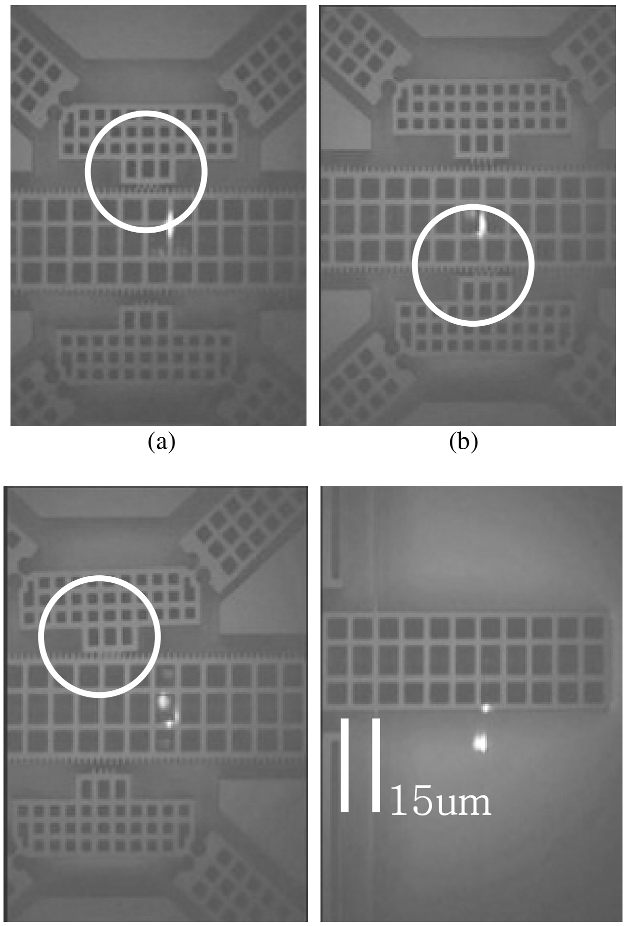
(c)

Figure 6. *Step signal and frequency response of the micromachined thermoelastic linkage actuators (a) tangential directional motion, (b) normal directional motion, and (c) tangential directional frequency response.*

Fig. 6(c) shows that the cutoff frequency response is about 250Hz by 50% of the amplitude criterion. By this cutoff frequency, we can estimate the maximum driving speed will be about 400 um/sec by the iterations of the pair of five-linkage actuators.

Driving characteristics of the fabricated micro inchworm motor were also experimentally investigated to evaluate its performance. First of all, the upper actuator A drove the shuttle mass one step, and the counterpart actuator B drove another step. Next the actuator A drove one more step and latched up the shuttle mass as shown in Fig 7(a),(b),(c) respectively. By three steps of the inchworm motion, the accumulated displacement was 15um as shown in Fig 7(d).

Using the fabricated micro inchworm motors, the gripping of a workpiece like an optical fiber is under investigation as shown in Fig. 8.



(a) (b) (c) (d)

Figure 7. *Video images of the inchworm motions, (a) 1st step by top actuator, (b) 2nd step by bottom actuator, (c) 3rd step and latch up by the top actuator, and (d) accumulated stroke of 3 steps. Notice the difference between the locations of the end effector in (a) and (c).*

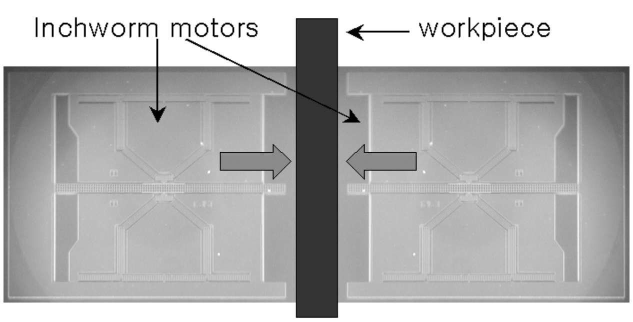


Figure 8. *Schematic of gripping a workpiece with one pair of the inchworm motors.*

CONCLUSION

A micromachined thermoelastic inchworm motor was fabricated and characterized for a large displacement with a high force. SOI wafers with the structural layer 40 um thickness were used to fabricate the proposed inchworm motors, and the inchworm motions were experimentally investigated by the cyclic motions. The maximum driving speed is estimated to about 400um/sec. The inchworm motor is applicable to the micro precision actuator for micro assembly or switching devices requiring the large displacement and the high force. As a further study, gripping a workpiece with the inchworm motors is under investigation.

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